Co-annihilating Dark Matter: Effective Operator Analysis and Collider Phenomenology

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Effective Field Theory Picture

- EFT formalism is useful to link results in dark matter searches in a model independent.

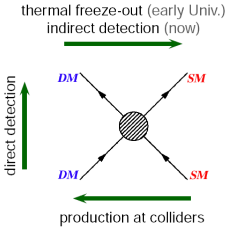


Figure: Link between different DM search strategies.

- EFT operators parametrise interaction of pair of DM particles (Dirac fermions) with SM particles, constrained by Lorentz and gauge invariance. Goodman et al.'10, '11, Dreiner et al. '13, Beltran et al. '10, Fox et al. '12

$$\frac{1}{\Lambda_{\text{eff}}^2}(\overline{\chi}\Gamma_1\chi)(\bar{f}\Gamma_2 f),$$

- Effective scale,

$$\Lambda_{\text{eff}} = \frac{M}{\sqrt{g_{SM}g_{DM}}},$$

with M mass of the heavy mediator and g_{SM} and g_{DM} the DM and SM particles coupling strengths.

EFT approach for co-annihilation

- Tension between lower limits on Λ_{eff} from direct detection (DD) and collider searches (mono-jet, mono-photon, mono-W/Z) and upper limits from sufficient annihilation in the early Universe Zheng et al.'12, Buckley '11
- $\Lambda_{eff} \gtrsim \mathcal{O}(100)$ GeV, EFT picture breaks down at LHC momentum transfer Busoni et al.'13.

  Apply similar study to a co-annihilation scenario, $\overline{\chi}_i \chi_j \to SM$, for $i, j = \{1, 2\}$.
- Relic density controlled by process involving χ_2, while direct and indirect detection involve χ_1 alone $\Rightarrow$ tension alleviated.
- Distinct collider signal due to $\chi_2 \to \chi_1 + SM$.
- Generalize standard EFT treatment with χ_1 and χ_2 are Dirac fermions,

$$\frac{1}{\Lambda_{11}^2}(\overline{\chi_1}\Gamma_1\chi_1)(\bar{f}\Gamma_2 f)\,, \qquad \frac{1}{\Lambda_{12}^2}(\overline{\chi_1}\Gamma_1\chi_2)(\bar{f}\Gamma_2 f) + h.c.\,, \qquad \frac{1}{\Lambda_{22}^2}(\overline{\chi_2}\Gamma_1\chi_2)(\bar{f}\Gamma_2 f)\,,$$

- Consider $\Gamma_1 = \Gamma_2 = \gamma_\mu$ and $\Lambda_{11} \gg \Lambda_{12}, \Lambda_{22} \Rightarrow$ DD only relevant if $\Delta m_\chi = m_{\chi_2} - m_{\chi_1} \lesssim 100$ KeV.
  $\therefore$ Only relic density and collider searches are relevant.

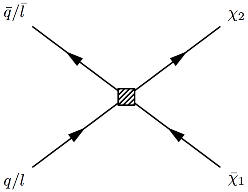
UV Completion

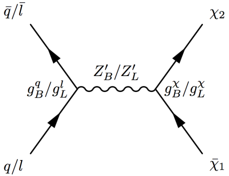
- EFT description can breakdown ⇒ simple UV completion introducing 2 neutral massive gauge bosons , Z'_B and Z'_L, associated with the spontaneous breaking of the gauged symmetries $U(1)_B$ and $U(1)_L$ respectively.
- Relevant interaction terms in the UV theory,

$$\begin{aligned} \Delta\mathcal{L}_{UV} &= g_B^q \bar{q}\gamma^\mu Z'_{B,\mu} q + g_L^l \bar{l}\gamma^\mu Z'_{L,\mu} l + g_B^\chi \left[\bar{\chi}_2\gamma^\mu Z'_{B,\mu}\chi_1 + h.c + \bar{\chi}_2\gamma^\mu Z'_{B,\mu}\chi_2\right] \\ &+ g_L^\chi \left[\bar{\chi}_2\gamma^\mu Z'_{L,\mu}\chi_1 + h.c + \bar{\chi}_2\gamma^\mu Z'_{L,\mu}\chi_2\right] , \end{aligned}$$

  where q and l represent the SM quarks and leptons.
- 2 effective scales,

$$\Lambda_{12,B} = \Lambda_{22,B} = \frac{M_{Z'_B}}{\sqrt{g_B^q g_B^\chi}} \,, \quad \Lambda_{12,L} = \Lambda_{22,L} = \frac{M_{Z'_L}}{\sqrt{g_L^l g_L^\chi}} \,.$$





DM relic density

- Effective annihilation cross-section Griest and Seckel '91, Edsjo and Gondolo '97,

$$\sigma_{\rm eff} = \frac{1}{(g_{\rm eff}/4)^2}\left[\sigma_{\chi_1\bar{\chi}_1\to f\bar{f}} + e^{-\Delta x}(1+\Delta)^{3/2}\sigma_{\chi_1\bar{\chi}_2\to f\bar{f}} + e^{-2\Delta x}(1+\Delta)^3\sigma_{\chi_2\bar{\chi}_2\to f\bar{f}}\right] ,$$

  where $x \equiv m_{\chi_1}/T$, $\Delta \equiv \frac{m_{\chi_2}-m_{\chi_1}}{m_{\chi_1}}$ and $g_{\rm eff} = 4 + 4e^{-\Delta x}(1+\Delta)^{3/2}$.

- Usual thermal freeze-out scenario apply non-relativistic expansion $\langle\sigma_{\rm eff} v\rangle \approx a_{\rm eff} + 6b_{\rm eff}/x \Rightarrow$

$$\Omega_{\chi_1}h^2 = \frac{1.07\times 10^9 {\rm GeV}^{-1} x_F}{g_*^{1/2} M_{Pl}(I_a + 3\frac{I_b}{x_F})} ,$$

  with $I_a = x_F\int_{x_F}^{\infty} dx\, \frac{a_{\rm eff}}{x^2}$ and $I_b = 2x_F^2\int_{x_F}^{\infty} dx\, \frac{b_{\rm eff}}{x^3}$.

- Implemented model in *FeynRules* and calculated relic density in *MicroMEGAs* in accordance to Planck results, $\Omega_{DM} = 0.1187 \pm 0.0017$.

- Scan assuming that DM only couples to quarks, $\Lambda_L \gg \Lambda_B$,

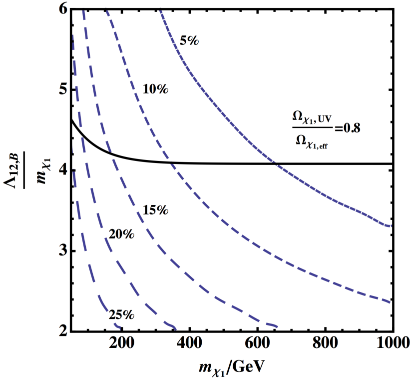


Figure: Contours of the mass splitting Δ which satisfy the correct DM abundance in the EFT approximation. Contours are shown with dashed lines for $\Delta = 0.05$, 0.1, 0.15, 0.2 and 0.25, as indicated. The solid line represents $\Omega_{\chi_1,\mathrm{UV}}/\Omega_{\chi_1,\mathrm{eff}} = 0.8$, where $\Omega_{\chi_1,\mathrm{UV}}$ is calculated taking $g_B^q = g_B^\chi = 1$. The EFT provides an adequate description for parameters above this line.

Coupling constraints from di-jet and di-lepton searches

- Direct production of the particle that mediates DM-SM interaction (Z'_L, Z'_B).
- Di-lepton searches at LEP-II. For $m_{Z'_L} > 200\ \mathrm{GeV}$, dilepton production through an off-shell mediator results in the bound $g^l_L \lesssim g^l_{L,max} \equiv 0.044 \times (m_{Z'_L}/200\ \mathrm{GeV})$.
- Z'_B parameters constrained by di-jet searches at hadron colliders (UA2, CERN SPS collider, CDF, ATLAS and CMS) $\Rightarrow$ limits in the $g_{Z'_B}$ - $M_{Z'_B}$ coupling-mass plane assuming Z'_B only decays into SM particles. Dobrescu and Yu '13 $\therefore$ decays into dark sector particles weakened the limits.
- Effect of the additional Z'_B decay modes is to increase the maximum allowed coupling to quarks by a factor of $1/\sqrt{\mathrm{Br}}$,

$$
\begin{aligned}
g^q_{B,max} &= g^q_B \frac{1}{\sqrt{Br(Z'_B \to jj)}} = g^q_B \left[1 + \frac{\Gamma(Z'_B \to \chi\overline{\chi})}{\Gamma(Z'_B \to jj)}\right]^{1/2}, \\
&\approx g^q_B \left[1 + \frac{r_B^2}{N_c N_f}\left(1 + 2\frac{m^2_{\chi_1}}{M^2_{Z'_B}}\right)\sqrt{1 - \frac{4m^2_{\chi_1}}{M^2_{Z'_B}}}\right]^{1/2},
\end{aligned}
$$

where $r_B = g^\chi_B / g^q_B$ and $m_{f,SM} \ll m_{\chi_1}, M_{Z'_B}$.

- Specifically, we take $g^l_{L,max} - g^l_L = 0.01$ and $g^q_{B,max} - g^q_B = 0.1$ with $M_{Z'_L} = 250, 500$ GeV

Collider phenomenology

- Lowest order $\bar{\chi}_1\chi_2$ production at LHC, $pp \to \bar{\chi}_1\chi_2 \to \bar{\chi}_1\chi_1 + SM$.
- Successful co-annihilation $\Rightarrow \Delta m \lesssim 0.3 m_{\chi_1} \Rightarrow$ soft momenta and small MET (approximately back-to-back χ_1 and $\bar{\chi}_1$). $\therefore$ Irreducible Z+jets background provides an enormous number of events hiding the signal.
- Imperative to break the back-to-back alignment for hidden particles $\Rightarrow$ hard jet in the form of initial state radiation (ISR).
- Process of interest at LHC $pp \to \bar{\chi}_1\chi_2 + j \to \bar{\chi}_1\chi_1 + SM + j$. Concentrate in di-lepton final state.

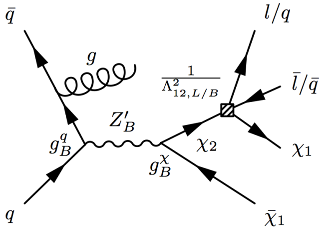


Figure: Contribution to the jet plus MET plus dilepton (or diquark) signal at the LHC.

Example points

m_{χ_1} (GeV)	m_{χ_2} (GeV)	$m_{Z'_B}$ (GeV)	g_B^q	g_B^χ	g_L^l	g_L^χ	$p_T(l_1)$ (GeV)	$M(l^+l^-)$ (GeV)	$\sigma_{pp\to\bar{\chi}_i\chi_j}$ 14 TeV (fb)	$\sigma_{pp\to\bar{\chi}_1\chi_1 l^+l^-}$ 14 TeV (fb)
250	270	525	0.15	0.80	0.045	0.66	–	< 20	6597	756
300	321	625	0.14	0.89	0.045	0.53	–	< 20	3694	504
400	420	825	0.18	0.68	0.045	0.32	< 40	< 20	905	136
600	612	1700	0.23	0.98	0.045	0.15	< 40	< 15	442	76
400	432	1375	0.21	2.2	0.11	0.8	–	< 30	2285	283
500	530	1500	0.18	1.83	0.11	0.52	–	< 30	1103	151
600	630	1475	0.16	1.61	0.11	0.36	< 40	< 30	852	96
700	728	1425	0.12	1.51	0.11	0.26	< 40	<30	193	22

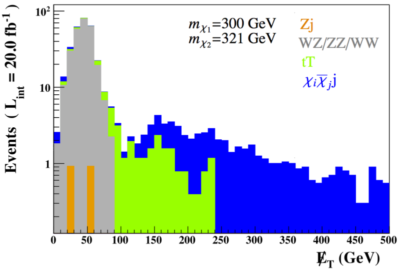
Backgrounds and event selection at the LHC

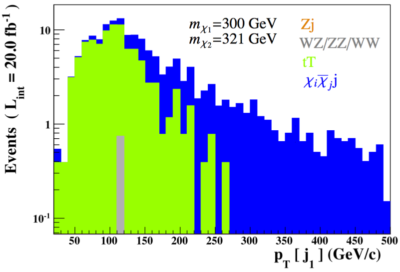
- Detail calculation of signal and background for $pp \to \overline{\chi}_1 \chi_2 j \to \overline{\chi}_1 \chi_1 j l^+ l^-$ using *MadGraph* 5 with built-in *Pythia* and *Delphes* to simulate the hadronization, showering and detector effects and doing the analysis with *MadAnalysis* 5.
- Trigger events demanding $\not{E}_T > 120$ GeV and $p_T(j_1) > 150$ GeV which makes $Z + jets$ background negligible.
- Another important background is top pair production, $t\bar{t} \to b\bar{b}l^+l^-\nu_l\bar{\nu}_l$, which can be reduced demanding $p_T(l_1) < 30 - 60$ GeV and no b-jet.
- Diboson pair production tend to be sub-dominant due to their smaller EW cross-sections.

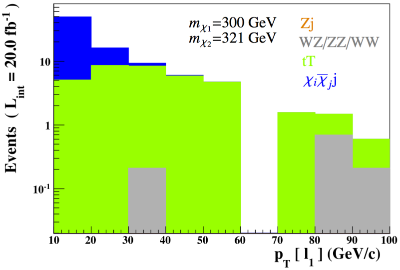
Cuts	Signal (S)	Background (B)	$S/\sqrt{S + \Delta B}$
$p_T(l) > 10$ GeV , $\lvert\eta_{lep}\rvert < 2.5$, $\Delta R_{l^+l^-} > 0.4$, $\Delta R_{lj} > 0.4$ $M(l^+l^-) > 5$ GeV	7520	1062935	0.10
$p_T(j_1) > 150$ GeV	1650	428354	0.04
$\not{E}_T > 120$ GeV	1079	22090	0.61
$M(l^+l^-) < 20$ GeV	55	85	3.8
$N(b) = 0$	53	38	5.2
$p_T(l_1) < 30$	52	14	6.3

Table: The cut-flow chart for example #2 with $\mathcal{L} = 20$ fb^{-1}. The cuts are sequential.

Histograms for example 2







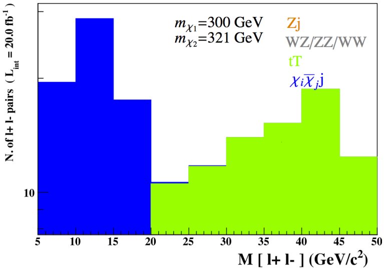


Table: Signal and Background after cuts for the example parameters with 10 % systematic error

Example #	$\mathcal{L}$ at $s = 14$ TeV	Signal (S)	Background (B)	S/B	$S/\sqrt{S + \Delta B}$
1.	$\mathcal{L} = 20$ fb^{-1}	67	14	4.8	7.4
2.	$\mathcal{L} = 20$ fb^{-1}	52	14	3.7	6.3
3.	$\mathcal{L} = 200$ fb^{-1}	106	137	0.77	5.1
4.	$\mathcal{L} = 300$ fb^{-1}	23	41	0.56	2.6
5.	$\mathcal{L} = 20$ fb^{-1}	159	93	1.7	8.6
6.	$\mathcal{L} = 20$ fb^{-1}	81	93	0.87	5.0
7.	$\mathcal{L} = 20$ fb^{-1}	51	63	0.80	4.1
8.	$\mathcal{L} = 300$ fb^{-1}	114	538	0.21	1.9

Other signals

- Mono-jet plus MET signals when χ_2 decays to neutrinos or the decays to quarks and leptons are too soft to be identified.
- Both strategies provide complementary information in the hunt for DM.
- Pair production of $\bar{\chi}_2\chi_2$, in $pp \to \overline{\chi}_2\chi_2 \to l^+l^-l'^+l'^-\bar{\chi}_1\chi_1$ results in two pairs of opposite sign-leptons, plus $\not{E}_T$
- Link between relic density constraint and strength of collider signal can be much less direct (double exponential suppression).
- Signal already being analysed by ATLAS still requires $\not{E}_T \gtrsim 50$ GeV $\Rightarrow$ again require ISR jet. ATLAS-CONF-2013-036
- $\sigma(l^+l^-l'^+l'^- + j + \chi_1\bar{\chi}_1) \sim (1/10) \times \sigma(l^+l^- + j + \chi_1\bar{\chi}_1) \Rightarrow$ non-negligible signal for $m_{\chi_1} \lesssim 600$ GeV.

Conclusions

- Examined a scenario in which dark sector contains two nearly degenerate particles: DM candidate χ_1 and a slightly heavier particle χ_2.
- Relic density determined via co-annihilation $\chi_1 + \overline{\chi_2} \rightarrow SM$, while direct and indirect detection processes are highly suppressed.
- Generalized standard EFT description to account the interaction of χ_1 and χ_2.
- Co-annihilation offers interesting new collider signals: standard mono-jet + MET searches, new signals due to $\chi_2 \rightarrow \chi_1\, l^+ l^-$ or $\chi_2 \rightarrow \chi_1\, q\overline{q}$.
- Simulated signal and background events for $l^+ l^-$ + jet + $\not{E}_T$ process for parameters that satisfy relic density constraints and di-lepton and di-jet searches, and demonstrated that LHC has the potential to identify these signals in forthcoming data.
- Scenarios with $m_{\chi_1} \lesssim 250$ GeV are already constrained by LHC measurements and even with $\mathcal{L} \gtrsim 20$ fb^{-1} we should be able to detect (or rule out) scenarios with DM masses below 300 GeV.